

Alien invertebrates are invading the Australian Alps

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Abstract

In temperate ecosystems, invasive alien species pose a major threat to species diversity. The first step in understanding likely ecological consequences of invasive species is to record new distributions. Three invertebrate species likely to affect Australian alpine and subalpine ecosystems are recorded for the first time above 1500 m ASL from the Victorian Alps: European Honey Bee *Apis mellifera* L., Grey Field Slug *Deroceras reticulatum* Müller, and European Wasp *Vespula germanica* (F.). Single records of other invasive alien species are mentioned but not explored. I present a simple online tool that is commonly used to model the distribution of species. Results show the value of extensive sampling, naturalist records and the need for reliable species distribution data. Building ecological models that can predict the likely consequences of invasive species is reliant on continual updating of historical species distribution records. (*The Victorian Naturalist* 130 (3) 2013, 127-136)

Keywords: Invasive species, European Honey Bee, Grey Field Slug, biodiversity, distribution modelling, European Wasp

Introduction

The interaction between climate change, human overexploitation and invasive alien species will reduce biodiversity in all temperate ecosystems. To avoid confusion with terminology used in research on invasive species (Colautti and MacIsaac 2004), and because all species discussed here are exotic to Australia, the term 'invasive alien' (Burke and Grime 1996) is used throughout. The current rate of extinctions is not being reduced because the pressures on biodiversity are intensifying (Secretariat of the Convention on Biological Diversity 2010). Due to anthropogenic activity, the function and resilience of ecosystems will change (Chapin III *et al.* 2000).

Biodiversity is thought to increase ecosystem resilience, as stated in the diversity-stability hypothesis (Loreau *et al.* 2003). The first step in understanding the importance of biodiversity is recording what fauna is present and where, but for terrestrial invertebrates these data are often lacking (Yen 2011). The recent shift in scientific concern regarding insect species extinctions, from polar to more temperate regions, highlights the importance of exotic incursions threatening ecosystem biodiversity (Deutsch *et al.* 2008). Despite a history of cattle grazing, which has ceased for now in National

Park areas of the Australian Alps (Williams *et al.* 2006), alpine ecosystems are relatively undisturbed by human activity in comparison to lowland ecosystems (McDougall *et al.* 2005). These alpine ecosystems are home to a high number of endemic plant species (Costin *et al.* 1982), but the alpine climate niche is not likely to exist beyond 2100 (Williams *et al.* 2007). Increased human activity, such as summer tourism and expansion of ski resorts, will further accelerate invasive processes (Pickering 2011). We need to record what species are present, to investigate how invasive alien species affect biodiversity, and their interaction with climate change (Hoffmann and Sgrò 2011) and land use intensification (Chapin III *et al.* 2000).

Species presence data from Australian museums are now readily available online through the Atlas of Living Australia (<http://www.ala.org.au>). Care is needed when using this resource with regard to alien invasive species because these species are nearly always considered pests and are not recorded despite being abundant. For example, in this study only two of the three invasive alien species had greater than the 50 records considered the absolute minimum for building models (Elith *et al.* 2011). The usefulness of online database tools

to provide informative baseline data relies on the continued observation and recording of changes to species distributions.

The Atlas of Living Australia website also provides a means to build simple species distribution models using Maxent, which can be used to estimate the relationship between a species and the environment across the known distribution. Maxent models are used widely to provide insights into evolutionary and ecological processes (Elith and Leathwick 2009; Elith *et al.* 2011) and formulate testable hypotheses. Using species distribution models, researchers can direct sampling efforts outside known distributions. For example, models of invasive alien species are often developed from their distributions in native environments and used to project likely distributions in non-native environments (e.g. Venette and Cohen 2006) and future environmental niches (Sutherst and Maywald 2005). However, the area (extent) being modelled must be relevant to the physiology of the species of interest. Hence, distribution models are often limited to the point of introduction and the new environments alien populations are likely to invade. Caution should be applied when modelling alien invasive populations because these are often not in equilibrium with their environment. That is, after a period of time invading populations decline to a lower level than the initial invading population (Hartley *et al.* 2010; Hill *et al.* 2012).

The aim is to record invasive alien invertebrates observed in the Victorian Alps above 1200 m ASL since 2010. Simple guidelines on using Atlas of Living Australia tools to build species distribution models are presented, and could support further surveys. The term 'alpine' as used throughout includes closed heathland, open heathland and grassland subalpine plant communities. This study will provide a record for future research.

Methods

To examine the threat invasive alien invertebrate species pose to indigenous alpine invertebrate communities, three species were considered further, based on recent observations: European Honey Bee *Apis mellifera* L. (Hymenoptera: Apidae) (Collett *et al.* 2007); Grey Field Slug *Deroceras reticulatum* Müller (Gas-

tropoda: Agrolimacidae); and the European Wasp *Vespula germanica* (F.) (Hymenoptera: Vespidae). Specimens from above 1200 m ASL were collected between 2010 and 2012, with voucher specimens retained at The University of Melbourne. The Geodetic (WGS84) location datum (latitude, longitude) was recorded using a hand held GPS receiver (Magellan® Triton400™, MiTAC International Corporation, Santa Clara, California USA).

The species distribution models presented were developed from historical Australian data because the species under consideration are established. Maxent (Phillips *et al.* 2006), as provided on the Atlas of Living Australia (ALA) web site (<http://www.ala.org.au/explore>), was used to predict suitable habitat for European Honey Bee and Grey Field Slug. Historical distribution records used were obtained from the Atlas of Living Australia (<http://www.ala.org.au/explore/species-maps/> 21 Mar 2012), Museum Victoria and Australian National Insect Collection. Before modelling, data were checked for consistency, with duplicate records and unverified locations removed. Over-sampling in locations that are easily accessible often leads to sampling bias, which affects model performance. There is no tool currently available to check sampling bias on the ALA website. Where sampling of Grey Field Slug was more intensive, as from Penola in South Australia with 130 records out of the total 457, the number of records was reduced. This sampling bias was taken into account by including a randomly selected subset ($n = 20$) of records from Penola in the model. Species misidentifications also reduce the usefulness of distribution records. To be sure of correct identification, the slug point localities were limited to the period that coincided with taxonomic revision (Van Regteren Altena and Smith 1975). In cases where there are limited distribution data, such as for European Honey Bee ($n = 53$), it was best to include all available data. In the case of European Wasp it was not possible to build distribution models because there was insufficient distribution data and a large sampling bias ($N = 12$ and large bias from Tasmania $n = 11$).

Environmental variables that influence habitat suitability for the species being modelled were based on known physiology, therefore

the literature was used to determine the initial variables used in models. For example, Grey Field Slug's optimum temperature for weight gain is 17°C–19°C, minimum temperature for activity is 0–5°C (Godan 1983; South 1982), maximum temperature for activity is 25°C (South 1982), and optimum gravimetric soil moisture for egg laying is 25% to 100% (Willis *et al.* 2008). Being opportunistic breeders, moisture and annual temperature, rather than seasonal temperatures, have been established as the most important variables in predicting slug populations (Choi *et al.* 2006). Climatic variables are often highly correlated and predictors need to be as proximal as possible (Elith *et al.* 2011), so bioclimatic variables derived from the monthly temperature and rainfall values (BIOCLIM) as provided on the ALA website were used. For Grey Field Slug the initial climatic variables chosen that were considered specific to this species were annual temperature, annual precipitation, precipitation-driest quarter, and annual moisture index. European Honey Bee populations need free water (Oldroyd *et al.* 1994), which suggests precipitation in the driest quarter would correlate highly with their distribution. Land use and vegetation type were included as initial variables because of the association of invasive alien species with humans (Crosby 2004), and European Honey Bee being farmed on native vegetation, an important nectar source (New 1994).

Species distribution model validation can involve complex statistical tests, such as cross-validation to obtain out-of-sample estimates of predictive performance and estimates of uncertainty around fitted functions (Elith *et al.* 2011); however, these are not facilitated by the ALA online tool. Assessment of model performance was limited. Variable importance was estimated using a jackknife test, run where each variable is excluded in turn, and a model created with the remaining variables. A model was also created using each variable in isolation. Subsequent jackknife plots were generated to visualise how individual variables improve the model. The most informative variables were used to build the model quantified by calculating the Area Under the receiver operating Curve (AUC). To validate models, a random sample comprising 25% of the data was used as test data and the

standard error calculated for the AUC. Overall model performance was assessed by using a receiver operating curve (ROC) for both the data used to build the model and data set aside to test the model. The aim was not to project species distributions onto novel environments but to determine the variables used (Elith *et al.* 2011) in the final models (Fig. 1 and 2). The final set of informative variables used in the models was obtained by removing variables with low influence on the model. New observations (Tables 1 and 2) above 1200 m ASL were used to validate models.

Results

The first recorded observation of the European Honey Bee above 1500 m ASL in the Victorian Alps is from early 2010, 5 km from the Falls Creek resort. Observations in 2012 indicated that European Honey Bee range extends across the Bogong High Plains (up to 1825 m ASL), including Mt Bogong, with one voucher collected from Quartz Ridge (1541 m ASL), where high numbers were seen foraging on *Styloidium* sp. Sw. (Table 1). No previous records for the Victorian Alps were found from museum records searched (106) with the closest record (HYM35167) at Merrijig. In January 1972 Jones (1972) observed Honey Bee visiting *Prasophyllum alpinum* R.Br on Rocky Plain, near Wulgulmerang approximated at 1200 m ASL, and in 1984 Inouye and Pyke (1988) recorded three individuals within the Kosciuszko National Park above 1860 m ASL. These observations were supported by the distribution model (Fig. 1), which suggested that suitable habitat for the European Honey Bee has existed throughout the alpine and subalpine landscapes of the Australian Alps. The environmental variables used in the final model and their importance (in per cent) were: precipitation-driest quarter (Bio17), 49%; temperature-annual mean (Bio01), 43%; present vegetation 8%; AUC 0.885; test AUC of 0.901 (std. dev. 0.05).

The highest recorded observation of Grey Field Slug in the Victorian Alps is now 1650 m ASL, from Basalt Hill, Bogong High Plains (Table 2). A number of new observations are from higher elevations than previously recorded in Victoria. Museum Victoria records (640) indicate Grey Field Slug have been widespread for a

Table 1. Observations (2010–2012) of European Honey Bee *Apis mellifera* L. above 1400 m ASL.

Date	Lat	Long	m ASL	Plant species observed visiting
17 Feb 10	-36.8652	147.2792	1595	<i>Trifolium repens</i>
17 Feb 10	-36.8696	147.2541	1660	Not recorded
15 Dec 11	-36.8648	147.3326	1725	Not recorded
13 Jan 12	-36.8479	147.3378	1802	<i>Poa hiemata</i>
13 Jan 12	-36.8463	147.3365	1825	<i>Trifolium repens</i>
18 Jan 12	-36.7137	147.2951	1445	Not recorded
19 Jan 12	-36.7563	147.3267	1775	<i>Trifolium repens</i>
19 Jan 12	-36.7629	147.2912	1541	<i>Styloidium</i> sp.

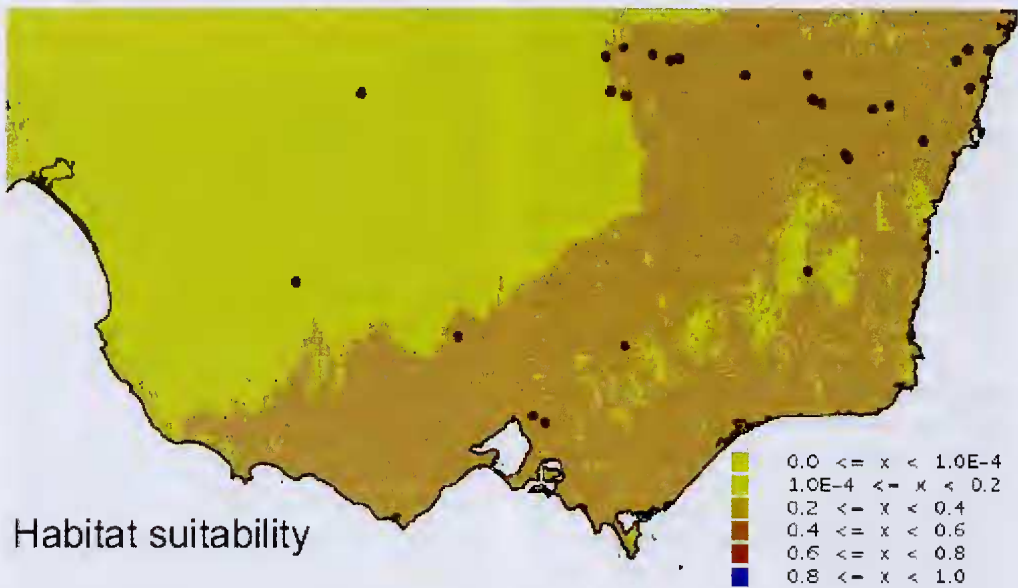


Fig. 1. A representation of the distribution model for the European Honey Bee *Apis mellifera* L. from museum records (brown dots). Warmer colours (orange) show areas with more suitable habitat conditions; yellow is least suitable.

considerable time at lower elevations. The highest elevations previously recorded include 1250 m ASL at Mt Donna Buang (F174393) in 1971 and seven records from 700 m ASL at Bogong Village (F174318, F174443, F 174474, F174535, F174587, F174619, F 177195). The recent record (2 Mar 2011) at 1591 m ASL from Kosciuszko National Park (Table 2) is also at a higher elevation than those recorded from 1975 along the snow road from Jindabyne to Charlotte Pass, (F174659, F174665, F174667) at 1470 m ASL, 1529 m ASL, and 1555 m ASL.

The most suitable habitat for Grey Field Slug was projected to be temperate areas with high

moisture availability at lower elevation (Fig. 2). Sample bias may have influenced the model presented (Fig. 2), despite adjusting for the high concentration of records from a southeast South Australia survey. The environmental variables used in the final model and their importance (in per cent) were: temperature-annual mean (Bio01), 94%; precipitation-driest quarter (Bio17), 4%; annual moisture index (Bio28), 2%; AUC 0.973; test AUC 0.975 (std. dev. 0.003).

The first recorded observations of European Wasp above 1500 m ASL in the Victorian Alps are from along the side of Road 23 (36.8684S

Table 2. Observations (2011–12) of Grey Field Slug *Deroceras reticulatum* Müller above 1200 m ASL.

Date	Lat	Long	m ASL	Recorded from
16 Feb 11	-36.8855	147.3158	1647	<i>Poa hiemata</i> grassland
1 Mar 11	-35.8895	148.5196	1417	<i>Poa</i> spp. and <i>Austodanthonia</i> spp.
1 Mar 11	-36.1598	148.6871	1204	<i>Themeda</i> sp. grassland
1 Mar 11	-35.8745	148.6241	1340	<i>Themeda</i> sp. and <i>Poa</i> spp. grassland
2 Mar 11	-36.3808	148.4578	1591	<i>Agrotis</i> sp. roadside
1 Mar 11	-36.1238	148.6477	1247	<i>Themeda</i> sp. roadside
21 Mar 11	-36.8709	147.3072	1630	<i>Agrotis</i> sp.
7 Apr 11	-37.7070	145.6816	1250	<i>Holcus lanatus</i>
18 Jan 12	-36.8866	147.3181	1638	Tiles
15 Feb 12	-36.9944	147.1644	1650	Tiles

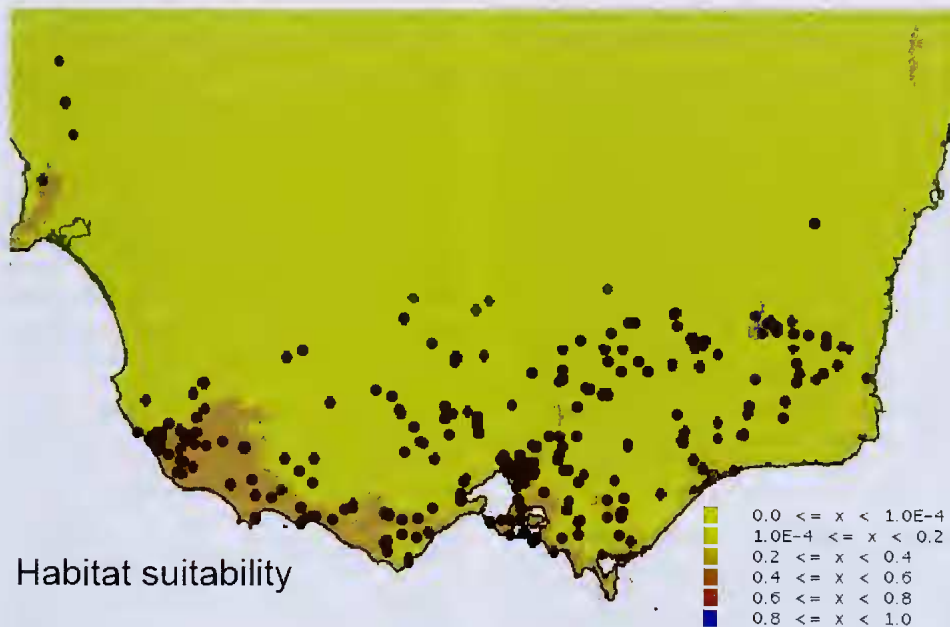


Fig. 2. A representation of the distribution model for the Grey Field Slug *Deroceras reticulatum* Müller from museum records (brown dots). Blue and warmer colours show areas with more suitable habitat conditions; yellow is least suitable.

147.241E, 1545 m ASL) 17 Feb 2010 and Ropers Hut (36.8121S 147.3311E, 1725 m ASL) 1 Mar 2010. A search of Museum Victoria records and ALA found only one record for Victoria, from Melbourne (37.8 S 144.98E), and 11 records for Tasmania, none of which were above 1000 m ASL.

Single records for other alien invasive species encountered in the past three years were Hedgehog Slug *Arion intermedius* (Normand) (Arionidae) at Smiggin Holes, N.S.W. (36.3876S

148.4270E, 1735 m ASL) 3 Mar 2010 on *Poa* spp., Striped Field Slug *Lehmannia nyctelia* Bourguignat (Limacidae) from NSW (35.8003S 148.6761E, 1213 m ASL) on Kangaroo Grass *Themeda triandra* (R.Br.) Stapf grassland 1 Mar 2011 and an European Earwig *Forficula auricularia* L. (Dermaptera: Forficulidae) at Basalt Hill (36.8855S 147.3158E, 1647 m ASL) 16 Feb 2010 from Soft Snowgrass *Poa hiemata* Vickery grassland.

Discussion

Observations since 2010 support the hypothesis that suitable niches above 1500 m ASL in the Victorian Alps are now occupied by European Honey Bee, Grey Field Slug and European Wasp. These new records add to the list of exotic invertebrate species already established in the Australian Alps: Cabbage White Butterfly *Pieris rapae* L. (Lepidoptera: Pieridae) and Rutherglen Bug *Nysius vinitor* Bergroth (Hemiptera: Lygaeidae) (Green and Osborne 2012). More alien species records are expected from alpine areas, because widespread pests found at lower elevation could have been overlooked for several reasons. Such reasons include: common species not being collected because they are common (e.g. European Wasp), no monitoring of invasive aliens outside the agricultural ecosystems where they are considered pests (e.g. Rutherglen Bug), expanding ranges due to adaptation to new environments, changing biotic interactions, or shifting environmental niches due to climate change. Given that at least two of the alien species (European Honey Bee and Grey Field Slug) have only recently been recorded in the Victorian Alps and simple species distribution models suggest that the Victorian Alps provide suitable habitat, the potential ecological consequences of these two species are discussed in detail, followed by a more general discussion of other threats.

Alien Pollinators: European Honey Bee

The observations of European Honey Bee from 2011–12 across subalpine and alpine habitats are a concern, given only native bees (Halictidae and Colletidae) were observed visiting native flowers during previous studies in the Victorian Alps (Nash, unpublished data 2008–09). *Pimelea lingustrina* Labill. flowering at Kosciuszko National Park was occasionally visited by European Honey Bee (< 1% of observations) (Inouye and Pyke 1988). That European Honey Bee have not dispersed sooner throughout the Australian Alps and exploited alpine and subalpine floral resources is surprising. European Honey Bee have expanded from their native homes in Europe, Asia and Africa, establishing across most of the world. European Honey Bee are perhaps Australia's most widespread invasive alien invertebrate, found in nearly all

terrestrial habitats (Low 1999). Because of European Honey Bee's economic importance, humans actively aid their extensive spread, with commercial hives introduced to Australia in 1822 (New 1994). The human-aided dispersion is supported by the model presented, which projected high habitat suitability in urban and rural residential areas. Habitat suitability is also dependent on the availability of free water (Oldroyd *et al.* 1994), with the model presented supporting this as precipitation in the driest quarter was a highly informative variable. The observations in the Victorian Alps correspond with wet summer conditions in 2011–12. Bureau of Meteorology data at Falls Creek for both years is in the 90th percentile for rainfall. Distribution modelling using historical data does not support occurrence being due to wet seasonal conditions.

Despite European Honey Bee being active invaders (New 1994), their impacts are debated (Collett *et al.* 2007), and we do not know what ecological effects they are having. Spessa's (2000) views are clear: European Honey Bee populations should be eradicated from conservation areas with high endemism. Such a concern stems from studies into competition by European Honey Bee for floral resources (Manning 1997), and a decline in native nectar feeders (Paton 1993), although some studies suggest limited resource competition (Schwarz and Hurts 1997). Other possible competitive interactions include displacement of birds (Oldroyd *et al.* 1994) and mammals that use tree hollows for breeding (Oldroyd *et al.* 1997). If and how these invasive alien colonies interact with numerous, and often solitary, native bee species is not well understood. The invasive aliens could even act as a vector for novel viruses to native bee populations (New 1994).

The biggest unknown ecological impact of European Honey Bee is pollination of native plants, which could change in several different ways. European Honey Bee may increase the transfer of pollen between flowers, leading to greater seed production (Paton 1997); displace existing pollinators, potentially reducing seed production (Celebrezze and Paton 2004); alter the behaviour of indigenous plants, resulting in unknown seed production response; or remove pollen, thereby reducing seed production

(Paton 1993). These and other unspecified and unknown effects are likely to occur in combination (Collett *et al.* 2007). Before any conclusions can be made about negative or positive effects, further research is required (Paini 2004). The genetic consequences of reduced pollen transfer and seed production include inbreeding depression, which reduces a species' ability to adapt (Sgrò *et al.* 2010). For example, in Gully *Grevillea barklyana* (F. Muell. ex Benth.) flowers that were out-crossed produced significantly more seed. Low out-crossing rates within some populations reflected the presence of introduced pollinators (Ayre *et al.* 1994). However, by increasing the transfer of pollen, European Honey Bee may improve gene flow among isolated plant populations, thus increasing their ability to adapt to perturbations, such as climate change (Hoffmann and Sgrò 2011; Sgrò *et al.* 2010). Currently, whether these processes already occur or are likely to occur, and in what combination(s), remains unknown. This is worrying because the European Honey Bee is already present in the Australian Alps and the distribution models presented here show that much of the alpine and subalpine landscape provides suitable habitat.

Invasive Alien Herbivores: Grey Field Slug

Aided by human destruction of lowland native vegetation, exotic slugs have become established throughout temperate Australia (Smith and Kershaw 1979), ensuring grasslands will remain altered (Holland *et al.* 2007). There is a small number of native Slug (Eupulmonata) species in Australian ecosystems, with only three endemic families: Athoracophoridae, Cystopeltidae and Rathouisiidae. None of these are found in alpine heathlands or grassland plant communities (Daniell 1994). The first record of exotic slugs in Australia was from 1824 with the six families noted: Agrolimacidae, Arionidae, Limacidae, Milacidae, Testacellidae and Veronicellidae. The Grey Field Slug, along with other invasive alien species, is well established in remnant grasslands across western Victoria (Holland *et al.* 2007; Nash *et al.* 2007). A central issue of grassland ecology is the role herbivores play in the abundance of plants species (Crawley 1997). Slugs can change plant community composition (Frank 2003;

Hulme 1996) due to selective feeding (Edwards and Crawley 1999) and differing plant tolerance (Frank and Bailey 1999). The invasion of grasslands by exotic slugs is thought to reduce native forb recruitment by selective herbivory (Holland *et al.* 2007) and the lack of plant defences makes native species more susceptible to slug feeding (Daniell 1994). Australian alpine plants are not adapted to slug grazing, which will reduce seedling recruitment.

Invasive Alien Predators: European Wasp

European Wasp have some invasive potential in the Australian Alps National Parks (Coyne 2001), and have been observed in NSW Alps (Green pers. comm.). The European Wasp was first recorded from Sydney in 1954, the first nest was recorded from Tasmania in 1959 and the first nest from Melbourne was recorded in 1977 (Collett *et al.* 2007). The spread and establishment of nests was quite rapid, even though estimates of dispersal are low (730-815 m per season) (Crosland 1991), suggesting some dispersal is mediated by humans (New 1994). European Wasp are thought to prey on native invertebrate species, such as butterflies, but this is only anecdotal (Yen 2011). Unknown predatory effects of an invasive species on unknown alpine invertebrate species highlight the knowledge chasm confronting invertebrate conservation efforts.

Other Invasive Alien Invertebrates

Other invertebrates not yet recorded from the Australian Alps have become established in temperate grasslands, where they compete with indigenous invertebrates. These species include: Julidan Millipedes (Diplopoda: Julidae) including the Portuguese Millipede *Ommatoiulus moreletii* (Lucas); Snails; and Tramp Ant (Collett *et al.* 2007).

Portuguese Millipede arrived in Australia 50 years ago, with Julidan populations continuing to expand their range. Portuguese Millipede are now an established invasive alien species, and they have likely altered the turnover of detritus by displacing native millipedes (Baker 1985). Other invasive alien Julidans that could pose a threat are Snake Millipede *Ophiyulus pilosus* (Newport), which have recently been recorded from Melbourne (2010) (Norton 2012). Exotic Julidans are well established in many parts of

the Tasmanian bush (Mesibov 2000), and may threaten native flora as they are herbivorous (Paoletti *et al.* 2007). Of approximately 2000 species of native millipedes, most are thought to be important detritivores in the Australian landscape (Black 1997), including alpine ecosystems. Given what is occurring in lowland ecosystems, it is expected that Julidan Millipedes have the potential to displace native alpine Polydesmids (Diplopoda: Polydesmida), altering the composition and turnover of dead plant material in grassland communities.

Despite ants (Formicidae: Hymenoptera) not being recorded from other alpine regions of the world (Green and Osborne 2012), their presence in Australian alpine ecosystems leads me to include an assessment of their invasive potential. The most abundant Ant species in the Australian Alps is Meat Ant *Iridomyrmex* spp. (Green 2002; Nash *et al.* 2013), which is a strongly competitive genus within the dominant Dolichoderinae functional group (Hoffmann and Andersen 2003). An example of Meat Ant dominance is their interaction with the invasive alien Argentine Ant *Linepithema humile* (Mayr). Since being recorded from Balwyn (Melbourne) in 1939, Argentine Ant have spread widely (Collett *et al.* 2007). In Australia mixed reports exist as to the extent of the change Argentine Ant cause to native ant communities (Clarke *et al.* 2008), but there is evidence of major negative responses in Australia (Heterick *et al.* 2000; Rowles and O'Dowd 2007; Walters 2006). For example, *Rhytidoponera victoriana* (Ponerinae) was displaced in peri-urban environments by Argentine Ant (Rowles and O'Dowd 2009). Argentine Ant have been recorded from Melbourne and surrounding areas in recent studies (Chong *et al.* 2011, Norton 2012), but low abundances exist because native Ant communities including Meat Ant are thought to outcompete them, except at one site where a super colony was known to have established (Norton 2012). Furthermore, in New Zealand, Argentine Ant populations have been shown to be in decline (Cooling *et al.* 2011). Given the dominance in numbers of the Meat Ant *Iridomyrmex mjobergi* Forel in the Victorian Alps (Nash *et al.* 2013) I concluded the threat of invasive alien ants to alpine ecosys-

tems is low compared to that of other invasive species.

The invasion of herbivores (slugs), predators (wasps) and pollinators (bees) into alpine ecosystems should not be ignored, if these unique environments are going to be conserved. Invasive alien plant species that have moved up into subalpine and alpine ecosystems (McDougall *et al.* 2005) are receiving some attention from management. Management should not consider exotic invasions in terms of individual species, but more as a community process comprising populations that adapt synergistically to new environments, aided by human disturbance (Crosby 2004). Lowland grassland ecosystems are irreparably changed, with only small remnants that are so fragmented they may not be conserved because they are unable to adapt or compete with established exotic communities (Hodgson *et al.* 2005). In the Australian Alps native populations have been able to outcompete alien exotic communities, but for how long can these isolated alpine ecosystems continue to do so? Continued vigilance is needed to track invasive communities that threaten the conservation of endangered indigenous species.

New records from the Victorian Alps expand the known distributions of a number of supposedly common invasive alien invertebrates. By adding to historical records, naturalists can help address the severe lack of distributional information. Only then can species distributions models reliably inform management of ecological processes that threaten unique Australian ecosystems.

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References

- Ayre DJ, Whelan RJ and Reid A (1994) Unexpectedly high levels of selfing in the Australian shrub *Grevillea barklyana* (Proteaceae). *Heredity* **72**, 168–174.
- Baker GH (1985) The distribution and abundance of the Portuguese millipede *Ommatoiulus moreletii* (Diplopoda, Julidae) in Australia. *Australian Journal of Ecology* **10**, 249–259.
- Black DG (1997) Diversity and biogeography of Australian millipedes (Diplopoda). *Memoirs of the Museum of Victoria* **56**, 557–561.
- Burke MJW and Grime JP (1996) An experimental study of plant community invasibility. *Ecology* **77**, 776–790.
- Celebrezze T and Paton DC (2004) Do introduced honeybees (*Apis mellifera*, Hymenoptera) provide full pollination service to bird-adapted Australian plants with small flowers? An experimental study of *Brachyoloma ericoides* (Epacridaceae). *Austral Ecology* **29**, 129–136.
- Chapin III FS, Zavaleta ES, Eviner VT, Naylor RL, Vitousek PM, Reynolds HL, Hooper DU, Lavorel S, Sala OE, Hobbie SE, Mack MC and Diaz S (2000) Consequences of changing biodiversity. *Nature* **405**, 234–242.
- Choi YH, Bohan DA, Potting RPJ, Semenov MA and Glen DM (2006) Individual based model of slug population and spatial dynamics. *Ecological Modelling* **190**, 336–350.
- Chong C-S, Thomson LJ and Hoffmann AA (2011) High diversity of ants in Australian vineyards. *Australian Journal of Entomology* **50**, 7–21.
- Clarke KM, Fisher BL and LeBuhn G (2008) The influence of urban park characteristics on ant (Hymenoptera, Formicidae) communities. *Urban Ecosystems* **11**, 317–334.
- Colautti RI and MacIsaac HJ (2004) A neutral terminology to define 'invasive' species. *Diversity and Distributions* **10**, 135–141.
- Collett N, Lefoe G and Yen AL (2007) Invasive terrestrial invertebrates in Victoria. *The Victorian Naturalist* **142**, 87–107.
- Cooling M, Hartley S, Sim DA and Lester PJ (2012) The widespread collapse of an invasive species: Argentine ants (*Linepithema humile*) in New Zealand. *Biology Letters* **8**, 430–433.
- Costin AB, Gray M, Totterdell CJ and Wimbush DJ (1982) *Kosciusko Alpine Flora*. 2 edn. (CSIRO Publishing: Melbourne)
- Coyne P (2001) Protecting the Natural Treasures of the Australian Alps. Report Australian Alps Liaison Committee.
- Crawley MJ (1997) Plant–herbivore dynamics. In *Plant Ecology*. Ed MJ Crawley. (Blackwell Scientific Publications: Oxford, UK)
- Crosby N (2004) *Ecological Imperialism: The Biological Expansion of Europe 900–1900*. (Cambridge University Press: Cambridge)
- Crosland MWJ (1991) The spread of the social wasp, *Vespula germanica*, in Australia. *New Zealand Journal of Zoology* **18**, 375–388.
- Daniell A (1994) The impact of terrestrial molluscs on native vegetation in south-eastern Australia. *The Victorian Naturalist* **111**, 218–222.
- Deutsch CA, Tewksbury JJ, Huey RB, Sheldon KS, Ghalambor CK, Haak DC and Martin PR (2008) Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences* **105**, 6668–6672.
- Edwards GR and Crawley MJ (1999) Herbivores, seed banks and seedling recruitment in mesic grassland. *Journal of Ecology* **87**, 423–435.
- Elith J and Leathwick JR (2009) Species distribution models: ecological explanation and prediction across space and time. *Annual Review of Ecology, Evolution, and Systematics* **40**, 677–697.
- Elith J, Phillips SJ, Hastie T, Dudik M, Chee YE and Yates CJ (2011) A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions* **17**, 43–57.
- Frank T (2003) Influence of slug herbivory on the vegetation development in an experimental wildflower strip. *Basic and Applied Ecology* **4**, 139–147.
- Frank T and Bailey SER (1999) Laboratory food choice trials to explore the potential of common weeds to reduce slug feeding to oilseed rape. *Biological Agriculture & Horticulture* **17**, 19–29.
- Godan D (1983) *Pest Slugs and Snails* (Springer Verlag: Berlin)
- Green K (2002) *Biodiversity in the Snowy Mountains*. (Australian Institute of Alpine Studies: Jindabyne, NSW)
- Green K and Osborne W (2012) *Field Guide to Wildlife of the Australian Snow-country*. (Reed New Holland: Chatswood, NSW)
- Hartley S, Krushelnycky PD and Lester PJ (2010) Integrating physiology, population dynamics and climate to make multi-scale predictions for the spread of an invasive insect: the Argentine ant at Haleakala National Park, Hawaii. *Ecography* **33**, 83–94.
- Heterick B, Casella J and Majer J (2000) Influence of Argentine and coastal brown ant (Hymenoptera: Formicidae) invasions on ant communities in Perth gardens, Western Australia. *Urban Ecosystems* **4**, 277–292.
- Hill MP, Hoffmann AA, Macfadyen S, Umina PA and Elith J (2012) Understanding niche shifts: using current and historical data to model the invasive redlegged earth mite, *Halotydeus destructor*. *Diversity and Distributions* **18**, 191–203.
- Hodgson JG, Montserrat-Martí G, Tallwin J, Thompson K, Díaz S, Cabido M, Grime JP, Wilson PJ, Band SR, Bogard A, Cabido R, Cáceres D, Castro-Díez P, Ferrer C, Maestro-Martínez M, Pérez-Rontomé MC, Charles M, Cornelissen JHC, Dabbert S, Pérez-Harguindey N, Krimly T, Sijtsma FJ, Strijker D, Vendramini E, Guerrero-Campo J, Hynd A, Jones G, Romo-Díez A de Torres, Espuny L, Villar-Salvador P and Zak MR (2005) How much will it cost to save grassland diversity? *Biological Conservation* **122**, 263–273.
- Hoffmann AA and Sgrò CM (2011) Climate change and evolutionary adaptation. *Nature* **470**, 479–485.
- Hoffmann BD and Andersen AN (2003) Responses of ants to disturbance in Australia, with particular reference to functional groups. *Austral Ecology* **28**, 444–464.
- Holland KD, McDonnell MJ and Williams NSG (2007) Abundance, species richness and feeding preferences of introduced molluscs in native grasslands of Victoria, Australia. *Austral Ecology* **32**, 626–634.
- Hulme PE (1996) Herbivores and the performance of grassland plants: a comparison of arthropod, mollusc and rodent herbivory. *Journal of Ecology* **84**, 43–51.
- Inouye DW and Pyke GH (1988) Pollination biology in the Snowy Mountains of Australia: Comparisons with montane Colorado, USA. *Australian Journal of Ecology* **13**, 191–205.
- Jones DA (1972) The pollination of *Prasophyllum alpinum* R.Br. *The Victorian Naturalist* **89**, 260–263.
- Loreau M, Mouquet N and Gonzalez A (2003) Biodiversity as spatial insurance in heterogeneous landscapes. *Proceedings of the National Academy of Sciences of the United States of America* **100**, 12765–12770.
- Low T (1999) *Feral Futures* (Viking: Ringwood, Vic)
- Manning R (1997) The honey bee debate: a critique of scientific studies of honey bees *Apis mellifera* and their alleged impact on Australian wildlife. *The Victorian Naturalist* **114**, 13–22.
- McDougall KL, Morgan JW, Walsh NG and Williams RJ (2005) Plant invasions in treeless vegetation of the Australian Alps. *Perspectives in Plant Ecology Evolution and Systematics* **7**, 159–171.
- Mesibov R (2000) An overview of the Tasmanian millipede fauna. *The Tasmanian Naturalist* **122**, 15–28.

- Nash MA, Griffin PC and Hoffmann AA (2013) Inconsistent responses of alpine arthropod communities to experimental warming and thermal gradients. *Climate Research* 55, 227–237.
- Nash MA, Thomson LJ and Hoffmann AA (2007) Slug control in canola: monitoring, molluscicidal baits and economic thresholds. *Pest Management Science* 63, 851–859.
- New TR (1994) *Exotic insects in Australia* (Gleneagles Publishing; Glen Osmond)
- Norton B (2012) The sanitisation of urban ecosystems: simplification of the ground layer in eucalypt woodlands and the effects on arthropod communities. Unpublished PhD thesis, The University of Melbourne)
- Oldroyd BP, Lawler SH and Crozier RH (1994) Do feral honey bees (*Apis mellifera*) and regent parrots (*Polytelis anthopeplus*) compete for nest sites? *Australian Journal of Ecology* 19, 444–450.
- Oldroyd BP, Thexton EG, Lawler SH and Crozier RH (1997) Population demography of Australian feral bees (*Apis mellifera*). *Oecologia* 111, 381–387.
- Paini DR (2004) Impact of the introduced honey bee (*Apis mellifera*) (Hymenoptera: Apidae) on native bees: a review. *Austral Ecology* 29, 399–407.
- Paoletti MG, Osler GH, Kinnear A, Black DG, Thomson LJ, Tsitsilas A, Sharley D, Judd S, Neville P and D'Inca A (2007) Detritivores as indicators of landscape stress and soil degradation. *Australian Journal of Experimental Agriculture* 47, 412–423.
- Paton DC (1993) Honeybees in the Australian Environment. *Bioscience* 43, 95–103.
- Paton D (1997) Honey Bee *Apis mellifera* and disruption of plant-pollinator systems in Australia. *The Victorian Naturalist* 114, 23–29.
- Phillips SJ, Anderson RP and Schapire RE (2006) Maximum entropy modeling of species geographic distributions. *Ecological Modeling* 190, 231–259.
- Pickering C (2011) Changes in demand for tourism with climate change: a case study of visitation patterns to six ski resorts in Australia. *Journal of Sustainable Tourism* 19(6), 767–781.
- Rowles AD and O'Dowd DJ (2007) Interference competition by Argentine ants displaces native ants: implications for biotic resistance to invasion. *Biological Invasions* 9, 73–85.
- Rowles AD and O'Dowd DJ (2009) Impacts of the invasive Argentine ant on native ants and other invertebrates in coastal scrub in south-eastern Australia. *Austral Ecology* 34, 239–248.
- Schwarz M and Hurts P (1997) Effects of introduced honey bees on Australia's native bee fauna. *The Victorian Naturalist* 114, 7–12.
- Secretariat of the Convention on Biological Diversity (2010) *Global Biodiversity Outlook 3*. Montréal.
- Sgrò CM, Lowe AJ and Hoffmann AA (2010) Building evolutionary resilience for conserving biodiversity under climate change. *Evolutionary Applications* 4, 326–337.
- Smith BJ and Kershaw RC (1979) *A field guide to the non-marine molluscs of south eastern Australia* (Australian National University Press: Canberra)
- South A (1982) A comparison of the life cycles of *Deroceras reticulatum* (Muller) and *Arion intermedius* (Normand) (Pulmonata: Stylommatophora) at different temperatures under laboratory conditions. *Journal of Molluscan Studies* 48, 233–244.
- Spessa A (2000) The buzz on honey bees. *Ranger: a journal for conservation managers* 50, 14–15.
- Sutherst RW and Maywald G (2005) A climate model of the red imported fire ant, *Solenopsis invicta* Buren (Hymenoptera: Formicidae): implications for invasion of new regions, particularly Oceania. *Environmental Entomology* 34, 317–335.
- Van Regteren Altena CO and Smith BJ (1975) Notes on introduced slugs of the families Limacidae and Milacidae in Australia, with two new records. *Journal of the Malacological Society of Australia* 3, 63–80.
- Venette RC and Cohen SD (2006) Potential climatic suitability for establishment of *Phytophthora ramorum* within the contiguous United States. *Forest Ecology and Management* 231, 18–26.
- Walters AC (2006) Invasion of Argentine ants (Hymenoptera: Formicidae) in South Australia: impacts on community composition and abundance of invertebrates in urban parklands. *Austral Ecology* 31, 567–576.
- Williams RJW, Wahren C-H, Bradstock RA and Muller WJ (2006) Does alpine grazing reduce blazing? A landscape test of a widely-held hypothesis. *Austral Ecology* 31, 925–936.
- Williams JW, Jackson ST and Kutzbach JE (2007) Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences of the United States of America* 104, 5738–5742.
- Willis JC, Bohan DA, Powers SJ, Choi YH, Park J and Gussin E (2008) The importance of temperature and moisture to the egg-laying behaviour of a pest slug, *Deroceras reticulatum*. *Annals of Applied Biology* 153, 105–115.
- Yen AL (2011) Melbourne's terrestrial invertebrate biodiversity: losses, gains and the new perspective. *The Victorian Naturalist* 128, 201–208.

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